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RADIATION ANALYSIS PROGRAM

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Final Report

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Research grant was designed to study radiation effects (total dose and upset) on modern electronics with the focus on what would provide the best capability for future spaceflight activities. This work also investigated the upsets associated with on orbit assets. Research resulted in an on orbit test platform that provides the ability to observe single event upset information on the International Space Station.

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1.0 Summary

This was a three-year activity for a total dollar amount of approximately $450,000. The focus of this work was to investigate new research areas related to radiation effects on modern electronics for space applications. Opportunities along the way allowed this project to actually end up with on orbit assets for performing radiation upset analysis. Other areas of research involved the development of a "lock step" microcontroller system to allow for beam testing of modern MSP-430 microcontrollers.

2.0 Introduction

The project was led by the researchers at the Configurable Space Microsystems Innovations and Applications Center (COSMIAC) Research Center at the University of New Mexico (UNM). COSMIAC is a Tier-2 research center at UNM that is devoted to the use of microprocessors and microcontrollers in education, training and in Low Earth Orbit (LEO) satellite development. COSMIAC developed two CubeSats for delivery to the National Aeronautics and Space Administration (NASA) in 2013/2014 and all of this proposed research built upon lessons learned from those two satellites and involved testing and characterization of existing systems.

COSMIAC used the provided funds to complete four major goals:

1. Design a wide variety of different platforms for testing. The goal of this activity was to understand the requirements that are necessary to be able to perform advanced radiation testing and to match that understanding with the skills available at COSMIAC in the areas of advanced microsystems for space applications.

2. Perform radiation analysis on created designs. The goal of this activity was to have a better understanding of the way changes in die size and width of traces/spaces on newly released electronic systems have changed the performance of radiation resiliency in new systems. The objective would be to take existing radiation test platforms and modify them so that they can be reused to perform new radiation testing and then to take the systems to the radiation sources and test for Total Dose failure.

3. Create a series of radiation hardened electronics with inexpensive design tools. The goal of this activity was to develop a way that the masses can create a series of radiation hardened electronics by design using very inexpensive design tools. The objective was to continue development of a core library of subsystems and to do the design with on hand design tools that cost under $2,000 and to eventually create a first run of an Application Specific Integrated Circuit (ASIC) chip that can be used in other projects

4. Present the results for public purpose. The goal of this activity was to achieve the public purpose. This will allow the team to be able to advise the larger nanosatellite community on what the best choices will be for utilization of modern electronics for space applications. The objective was to present at the CubeSat Workshop and the National Space Radiation Effects Conference (NSREC) when the COSMIAC team attends either of these two events as well as putting the results on the COSMIAC website.

3.0 Methods, Assumptions and Procedures

The University of New Mexico (UNM) proposed to perform research related to testing commercial systems for radiation robustness as well as the creation of radiation hardened parts for flight. There are a wide variety of new satellite missions and components that are being created based on a new class of satellites called CubeSats. These CubeSats are often flown in a LEO and are usually less than five kilograms in mass. Their low size, mass and limited lifetime means that inexpensive commercial electronics can be utilized for flight. There were more than 100 CubeSats launched in 2013. These small satellites are the wave of the future for research and development. The vehicles are now limited to LEO missions due to the fact that radiation hardened parts are required for higher altitudes.

3.1 Goal 1: Design a wide variety of different platforms for testing

The team created two different types of platforms for testing. The first is the Radiation Hardened Electronic Memory Experiment (RHEME) project (shown in Figure 1). RHEME-1 was designed to fly on the outside of the International Space Station (ISS) and collect radiation data. There are three overarching objectives of RHEME. The first is to collect on orbit radiation upset data as the system transits in the 400 kilometer orbit. The second is to bring RHEME-1 back to Earth in two years to perform a physical examination of the chips to investigate micrometeorite damage and finally, to find a way to miniaturize RHEME for future flights. RHEME-1 launched to the ISS in the fourth quarter of 2016. There has been such excitement on this experiment that future flights of the RHEME experiment are now scheduled.

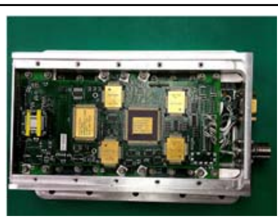

Figure 1: RHEME experiment

The RHEME-1 flight experiment was made to fit into the aluminum case shown in the Figure 1. This was a way to create an enclosure for withstanding the vibrational activities associated with launch without potential damage to circuit boards as well as providing a mounting capability on the ISS. The team designed the boards and the frame to hold the electronics. This included creating a rounded structure and larger connectors to accommodate astronaut's hands. The team performed space qualification testing to include vibrational, thermal bake and thermal cycling to ensure the experiment would perform as expected during operation on the ISS.

The team then proceeded to working on the second and third iterations of this flight article to allow for radiation testing at differing orbital altitudes and inclinations to determine where radiation belts and density of particles might exist. In August of 2016, RHEME-2 underwent a series of tests for flight qualification. These tests included bake and thermal cycling. In addition, vibrational testing was also accomplished.

As of March, 2017, RHEME-1 was orbiting on the ISS. Figure 2 shows astronauts placing the article on the outside solar panel of the space station. There were approximately four weeks of initial operational capability checks before the team began to obtain data they were comfortable in calling credible.

Figure 2: Beam Testing Design Paradigm

What is currently being processed is the various data as the system is switched between its different operating modes. Mode changes usually occur when the flight article has some reason to be reset. The power resets cause the system to default back to a specific mode of operation. Once that is identified and the root cause is explored, the system is then restored back to the operational mode required for daily research. Initial upset information is shown above in Figure 3. Even though the grant is expiring, this is an exciting and rich area of research for COSMIAC and an area where the data will continue to be available for the broader space community for the next several years. The team is already in discussions with other schools to do joint research on the RHEME data.

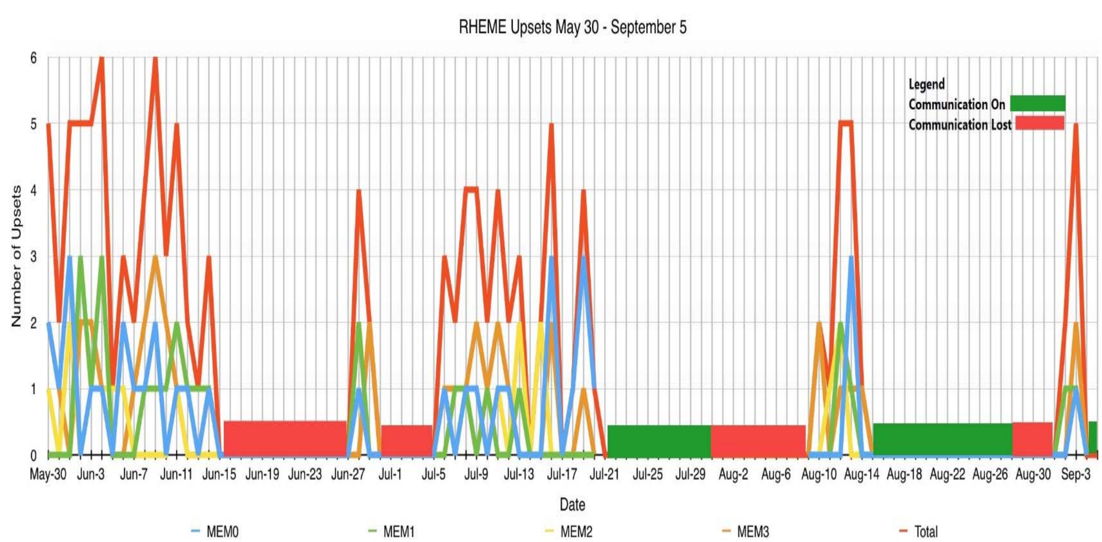

Figure 3: RHEME Upset History from May 30, 2017 to September 3, 2017

The second project advanced within this grant is related to beam and total dose testing of modern microcontrollers and electronics that are often used in space. The Texas Instruments Corporation has created an updated version of their MSP-430 microcontroller based on a new Ferroelectric Random Access Memory (FRAM) based design process. A prototype board is shown in Figure 4 that utilizes this FRAM chip. The older version of this controller is used on a large number of space missions. Many other CubeSats such as the NASA BioSentinel CubeSat mission are looking to fly the newer FRAM version of this part as their main motherboard/satellite control system. The COSMIAC team has already performed total ionizing dose (TID) testing of this hardware but TID testing provides only part of the answer on radiation effects knowledge. The other is related to the effects of upsets on electronic components. These other effects are referred to as Single Event Effects (SEE) and are caused by the collision of the electronic devices by highly energetic particles in space. For an item to be truly "radiation hardened" it must be able to withstand not only total dose but also SEE interference.

Figure 4: MSP430

SEE type testing and associated results are critical for all launch developers to know for proper planning and parts selection. To perform this type of testing, COSMIAC developed hardware and software to support the electrical portion of the testing. The first item created was a hardware interface platform that mated between the Xilinx Corporation's ZedBoard and the MSP-430 boards that were tested in an electron beam field. The second development is the firmware and hardware to test the MSP-430s. Figure 5 shows the hardware and software configuration that was utilized for beam testing of the MSP-430 microcontrollers.

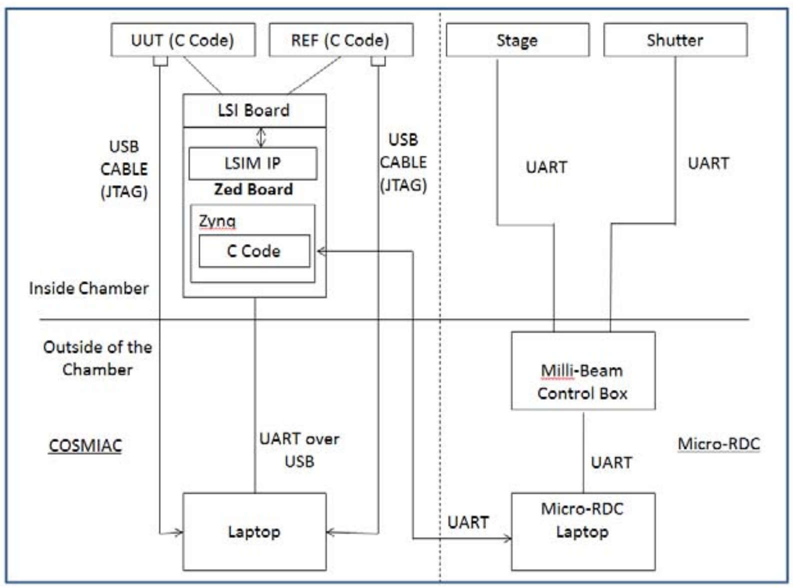

Figure 5: Beam Testing Design Paradigm

3.2 Goal 2: Perform radiation analysis on created designs

The team successfully performed beam testing at Berkeley, California to determine where the critical radiation paths are at within the MSP430 chips. The team has also been able to perform (and is scheduled to perform) radiation testing on the developed products. This TID testing was performed on advanced digital-to-analog (DtoA) and analog-to-digital (AtoD) devices. These new devices are very cutting edge and have the ability to change what can be accomplished in space. This research was performed as a joint activity with the SpaceX Corporation and the Air

Force Research Laboroatory (AFRL). SpaceX has access to these advanced AtoD and DtoA devices and provided them for free for testing purposes. The nanosatellite community sees these advanced parts as opening doors for faster and more accurate sensors in space applications if, the parts have enough radiation hardening resilience. This testing was accomplished utilizing the Cobalt radiation sources on Kirtland Air Force Base in August, 2016.

The team is using initial test result data to allow for developing collaboration efforts between AFRL and NASA on the creation of a list of commercial off the shelf (COTS) CubeSat systems where no or limited radiation information is available and to then use this information to be able to create a funding stream to allow for further testing be accomplished. The first portion of this research is the creation of a database of COTS components and then to begin creating a program and schedule for performing independent field tests on these items. This type of activity has spurred COSMIAC at UNM to staff and execute a cooperative research and development agreement (CRADA) between UNM and AFRL. This CRADA took 13 months to complete and developed the framework for future radiation testing opportunities for UNM that will provide the small satellite community with information for informed future flight parts selection. It will provide the community with radiation information for making more educated parts selection decisions.

3.3 Goal 3: Create a series of radiation hardened electronics with inexpensive design tools

The desire of this goal was to create a system that is deterministic, open source and be able to fit into a small electronic footprint while at the same time being inherently robust and radiation hardened. The team has developed projects using a very small processor called a J1. This processor is only several hundred lines of hardware descriptive language so will fit into a very small footprint on a Field Programmable Gate Array (FPGA) that is inherently radiation hardened (such as the Actel Corporations device). All source code for the J1 processor is openly available through Google. The processor is very deterministic but the initial learning curve to begin work on this processor is not trivial. The team spent months learning how to deploy the processor to a variety of different hardware platforms. The team then developed flight hardware to create a flight experiment using the J1 that will provide radiation effects and upset information on the developed article in a low earth orbit flight project. The project will hopefully be integrated and launched on future flights.

3.4 Goal 4: Present the results for public purpose

The team attended the HEART conference in the spring of 2015 as well as the CubeSat Workshop in 2016 where results of testing were discussed. The MSP-430 beam testing provided enough results to allow for a paper to be accepted and presented to the 2016 NSREC conference. Other publication opportunities are still being investigated.

4.0 Results and Discussions

The team achieved the original objectives as well as going into other areas of investigation that were of interest to the space community. The team met established goals. There were no cost overruns on this activity.

5.0 Conclusions

Four goals were achieved under this activity. The first goal was to design platforms as methods to characterize radiation response of computer processor components including the RHEME-1 experiment was designed and flown on the international space station as an ongoing space experiment. The experiment operates in various modes and has consistently downloaded data to ground. Follow-on experiments include retrieving the experiment from space and analyzing meteorite damage. An additional platform included radiation characterization of commercial processors. The second goal was accomplished by completing charged particle and ionizing radiation experiments of commercial off the shelf processors and memories. The third goal was achieved by leveraging a commercial processor that could be instantiated in a radiation hardened field programmable gate array, thus making a radiation hardened version of the processor available to small satellite designers. And finally, the results of this effort were published to interested parties of the satellite designer community at the HEART conference.

List of Acronyms

AFRL – Air Force Research Laboratory

ASIC – Application Specific Integrated Circuit

AtoD – Analog to Digital

COSMIAC – Configurable Space Microsystems Innovations and Applications Center

COTS – Commercial Off The Shelf

CRADA – Cooperative Research and Development Agreement

DtoA – Digital to Analog

FPGA – Field Programmable Gate Array

FRAM – Ferroelectric Random-Access Memory

ISS – International Space Station

LEO – Low Earth Orbit

NASA – National Aeronautics and Space Agency

NSREC – National Space and Radiation Effects Conference

RHEME – Radiation Hardened Electronic Memory Experiment

SEE – Single Event Effects

TID – Total Ionizing Dose

UNM – University of New Mexico

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